R98-35

*chapter twelve*

# Stored product quality: open dating and temperature monitoring

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## Introduction

The quality of a product held in storage will degrade over time, the rate of degradation being dependent on temperature. If the process associated with such degradation is highly sensitive to temperature, reflecting a high activation energy, the rate increases substantially as the temperature rises. Assuming that throughout the storage duration the temperature is maintained constant, a point in time will be reached when the product quality degrades, perceptively or imperceptively, to a level taken as a cutoff limit. That point in time corresponds to the product shelf life. In situations where the temperature is not constant, either because the temperature of the storage facility is uncontrolled and

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subject to fluctuations or because of malfunctioning temperature controllers, the cutoff quality will be reached in shorter or longer times. The dynamics underlying the quality degradation process and the modeling of the relationship to temperature and time are described in Chapters 11, 13, and 15 and are covered in detail in the book by Labuza[1] and in various journal articles.[2–5]

The quality cutoff limit and the shelf life under specific storage conditions vary over a wide range and depend on the nature of the product, the predominant degradation process, and the mode of storage. Roughly speaking, products can be classified as either fresh or processed, recognizing that there are gradations within and between these classifications. Minimal processing falls between the two, while commercial sterilization represents the extreme in processing. Roughly speaking again, the degradation processes can be classified as microbial, biochemical, and physicochemical. Growth of spoilage and pathogenic microorganisms, first and foremost, sets the limit on storage of fresh or minimally processed products. Biochemical processes, such as enzymatic browning and rancidity development, if occurring on a time scale shorter than microbial growth, can determine the cutoff. Physicochemical processes, including flavorant loss, moisture redistribution, and starch crystallization, some of which significantly affect texture, can determine the shelf life of products in which microbial growth is not a factor. Such biochemical and physicochemical instabilities are discussed in Chapters 3–6. Depending then on the susceptibility of the product to one or more of these degradation processes, it would be stored at freezing, chilled, or ambient temperatures to maintain a marketable quality for as long as is needed to move through the food chain from producer to consumer.

Even in a class of products made commercially sterile and storable at ambient temperature by thermal processing, there can be a wide range of shelf lives, as illustrated by studies on the storage stability of the prepackaged combat ration, Meal, Ready to Eat (MRE). In studies done in the 1980s,[6,7] the quality of MRE components stored at different temperatures from 2 to over 5 years depending on temperature was assessed by a consumer panel on the basis of a nine-point hedonic rating for overall acceptance and other sensory attributes. The data were analyzed by Ross et al.[7] in terms of the time it took (or would take) for the quality score to drop to a rating of 5 ("neither like nor disklike"). Although many components were used, the results were either pooled altogether or grouped into five categories: entrees, pastries, vegetables, fruits, and miscellaneous. Accordingly, the shelf life defined in this way for each group as a function of constant storage temperature can be plotted semilogarithmically,[8] as shown in Figure 1 for some of these categories, including the combination of all.

The distinctions among the products relative to their susceptibility to degrade and their sensitivity to temperature are clearly evident. Starch components, the pastries, have relatively short shelf lives that are almost independent of temperature. Fruits (i.e., dehydrated items) have relatively longer shelf lives at moderate storage temperatures, but much shorter shelf lives at higher temperatures, because of a high temperature sensitivity. The entrees are longer lived than either starches or fruits at moderate storage temperatures, but show shelf lives longer than fruits but shorter than starches at higher storage temperatures. These results emphasize the importance of knowing product sensitivity to storage temperature and time and the importance of being able to properly specify the cutoff limits in terms of end of storage times.

## Product dating

Providing consumers with information on a package that indicates how long it has been in storage or how soon it should be used is now an accepted practice. Such *product dating*

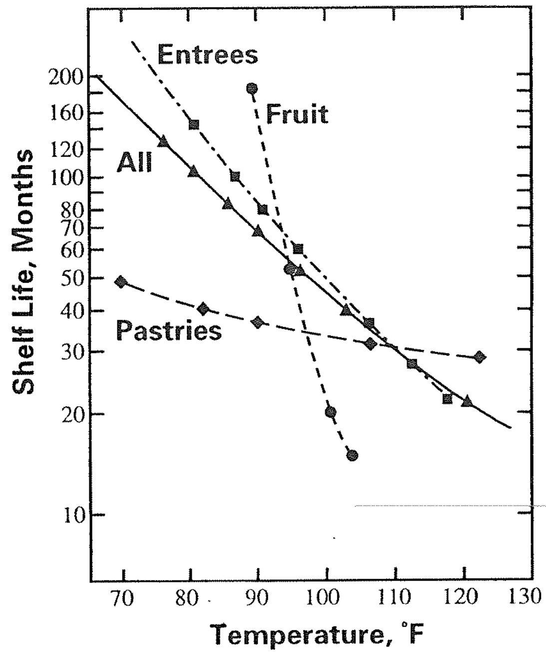



*Figure 1* Shelf life of MRE components as a function of storage temperature. "Shelf life" is defined here as the time in months for the rating to decrease to 5 on the hedonic scale. The line for "All" (▲) corresponds to the pooling of data for all components.

or *open dating*, however, varies in terminology and is not always easily understood. Some of the terms used include "Pull Date," "Use by Date," "Sell by Date," "Best if Sold by Date," "Better if Used by Date," "Best When Used by Date," and "Date of Pack." Sometimes just the date corresponding to 3 years in the future will be stamped on the package or can. Clearly, terms that indicate the date to sell the product are aimed at the retailer, but the consumer relies on them as well.

Product dating, if properly understood, minimizes but does not eliminate the possibility of purchasing and consuming a spoiled or significantly deteriorated product. The *sell by* terms tend to imply that the food suddenly becomes unacceptable by that date and should be discarded. The *best if used by* terms avoid this perception and tend to imply a more gradual deterioration. In either case, such date designations cannot guarantee that a spoiled product will not be bought or consumed, because the reference temperature is not provided and the temperature history is not known. Their limitations notwithstanding, they do serve as a useful guide to the consumer when purchasing the product from the retailer and when using it while stored at home.

In practice, the best way to assure that a product will be safe and of an acceptable quality when consumed is to control temperature during storage and distribution and to integrate the temperature exposure over time.

## Temperature monitoring

### Monitoring devices

The devices and procedures used to monitor or control the temperature in a storage or transportation facility depend on the product and the location of the product in the distribution chain. Thermometers such as the mercury-in-glass type can provide an accurate measurement of the temperature, but only on an instantaneous basis. Generally, one would need to take thermometer readings on a regular basis to obtain meaningful data on the temperature history. This approach would involve considerable labor, so in most cases a recording thermometer, or thermograph, is used. Such an analog recorder can be useful both in determining if a certain temperature had been exceeded and in providing feedback for regulating the temperature. Analog recorders now are being supplanted by digital recorders, including battery-powered portable devices, that not only sample the temperature at adjustable intervals, but store the information for subsequent downloading to a computer. Through available programs, the sampled data can be printed out in various formats or utilized for further analysis, including integrating temperature over time and correlating product quality with such an integration.

### *Monitor placement*

The distribution of food products occurs over a wide geographic area and can involve multiple modes of transportation and diverse warehousing in urban as well as in rural areas. Storage of military rations, in particular, includes facilities in remote and sometimes forbidding regions. The complex nature of the distribution system and the wide range of daily and seasonal temperatures impose significant stresses on the products that need to be monitored.

Transportation to and from warehouses in the chain often involves a combination of land, sea, or air transport. Each loading and unloading operation at a transfer point or interim storage facility introduces a thermal stress or an excursion from an otherwise controlled temperature environment. Moreover, each mode of transport would not usually be designed for extremes in temperature, which put a greater load than expected on the temperature control systems. Often the amount of product that is transported comes close to the volumetric limit of the transport, especially in the case of trucks. Although their cooling systems work more efficiently when near design capacity, the temperature of the product when loaded onto such transporters can introduce a heat load that causes the capacity to be exceeded. Even if the equipment continues to function properly, the added heat load requires a longer time for the product to reach its set temperature and, in some cases, the product could reach its destination without having attained the proper temperature. This excursion from the desired temperature can easily happen aboard ships where the chill boxes are filled to capacity and the destination is a hot climate.

Under such circumstances, the placement of the monitoring/recording devices becomes critical if the record is to be representative of the thermal history of products being transported and stored. Since the cost of the portable recorders is significant, the number that can be used in an individual shipment is limited. Ideally, they should be packed in cases placed in strategic locations on pallets placed strategically within a van to capture both the most stable environment as well as the most fluctuating environment (e.g., near the door of the container van).

All products will be stressed in some way during such distribution, but they will not necessarily be abused. There will always be normal variations in temperature during the life cycle of a product. Even in a freezer or refrigerator, there is an expected fluctuation in temperature above or below which a deteriorative effect can occur. When this upper temperature limit is exceeded or when, in the case where freezing is to be avoided, the lower limit is exceeded, then the product might be abused. The degree of abuse would depend on the length of time the product is beyond the limit and the tolerance used in setting the limit.

## Time–temperature indicators

Time–temperature indicators (TTIs) can be either full history or partial history temperature monitors that integrate the exposure to a temperature over time by accumulating the effect of such exposures. TTIs of either type usually require activation at start-up time. The full-history TTI will integrate continuously until it has expired. The partial-history TTI will integrate only when the temperature exceeds a predetermined set point, e.g., 90°F; moreover, when the temperature returns to or passes through the set point, the integrating ceases. TTIs have different, sometimes adjustable, sensitivities to temperature, which correspond to different reaction rate constants and activation energies. A discussion of the kinetics as well as other aspects of using TTIs is provided in a paper by Grabiner and Prusik.[9] More details on TTI devices are in a paper by LeBlanc,[10] especially related to their application with frozen foods. A TTI standard has been developed by ASTM.[11]

### Principle of operation

TTIs can be classified on the basis of the phenomenological processes that governs their principle of operation. These phenomena include enzymatic or nonenzymatic chemical reactions and various physical transformations. With respect to chemical reactions, the original I-Point TTI was based on the enzymatic hydrolysis of a fatty acid ester, which leads to a change in pH that would be discernible through a color change in a pH indicator. The LifeLines TTI, to be discussed in more detail below, is based on the thermally induced polymerization of a substituted diacetylene monomer, which leads to a change in color and optical reflectivity. With respect to physical processes, the 3M TTI is based on diffusion of a dye in a material whose viscosity decreases with increasing temperature, which leads to a migration of the dye front along a linear strip. In all cases, the monitoring and integration relies on a temperature-dependent phenomenon that can be made to give a visual indication by a color change or color migration.

The review by Taoukis et al.[2] includes a discussion of TTI classification and principles. It also summarizes patents in the field. Depending on the principle, the TTI label is configured so that the integrated effect can be assessed. With some labels, an instrumental reading of change in color intensity can be made that gives a quantitative value of the time–temperature integration. Some labels are designed so additional information about the product to which it is attached can be obtained in order to facilitate a computer-based product management system.

### Integration concept

The concept of an integrating indicator label, though based directly on kinetic principles, can be pictorally illustrated using a ticking clock analogy (Figure 2). The ticking rate depends on temperature and the accumulated number of ticks corresponds to the integrated effect. In this illustration, frame A shows an arbitrary ticking rate at 60°F of 1 tick/min that doubles every 10°F, frame B shows two temperature profiles, 1 and 2, over a 2-hour period, and frame C shows the accumulation or integration of ticks for each profile. Note that the time-averaged temperature for both profiles is 80°F. Nevertheless, the total number of ticks for profile 2 is greater than for profile 1, because of the larger residence time at 100°F. This simple depiction merely follows the very detailed and often sophisticated treatments of nonisothermal kinetics obeying the Arrhenius relation, but it emphasizes pictorially the influence of high temperature exposure time on the overall thermal effect.

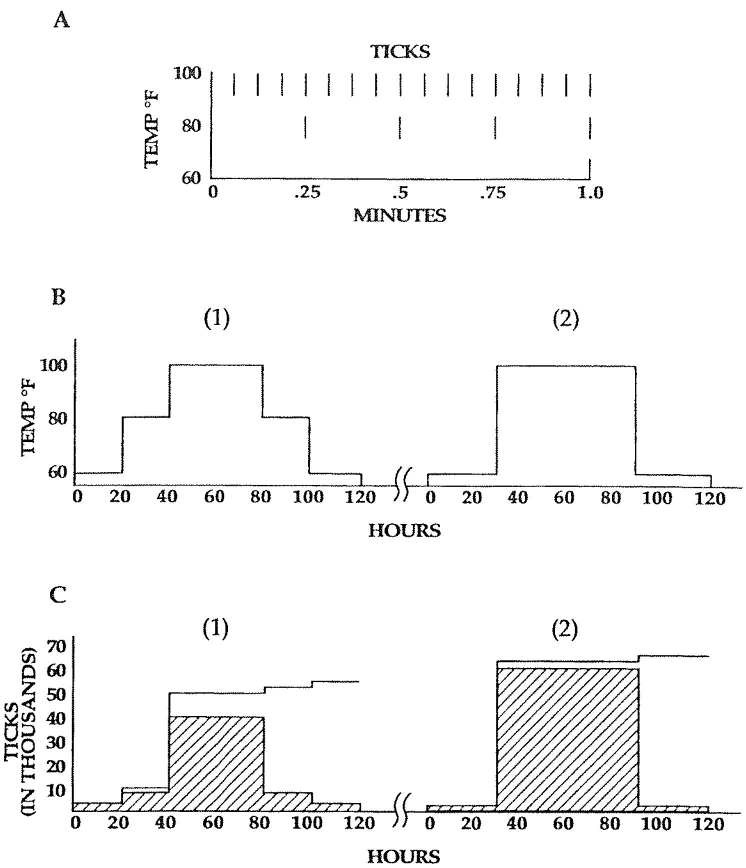



*Figure 2* Pictorial representation of the integration concept. Frame A depicts the interval between ticks for each temperature, and indicates that the ticking rate at 100°F is 16 times the rate at 60°F. Frame B depicts two different temperature profiles; the mean temperature is 80°F for both profiles 1 and 2. Frame C depicts the number of ticks for each time interval (the shaded area) and the accumulated number of ticks (the upper line) at the end of each time interval. The total number of ticks is 50,400 and 61,200 for profiles 1 and 2, respectively. This difference in tick count corresponds to a decrease in shelf life of about 18%.

## *Illustrative applications*

TTIs have been used in diverse applications to track thermal exposure and to signal the associated degradation in the product. A common feature is that there is at least one attribute of the product that undergoes a temperature-dependent change responsible for, or related to, a decrease in product quality with time. In the applications to be described, a TTI label that indicates visually was used.

The label (Figure 3), produced by LifeLines, consists of three main sections: a bar code both for identifying the label (a serial number in this instance) and for providing additional information (including product code), a bar code to represent the thermally sensitive material used as the indicator (MC38 in this instance), and a stripe or patch containing the indicator material which is applied in a printing process. A computer-based scanner is used to obtain the digital signals from the bar codes and the analog signal from the stripe on each label. Since the scanner is responding to the light intensity reflected by the stripe, this analog signal is transformed into *percent reflectance*. As the stripe darkens with

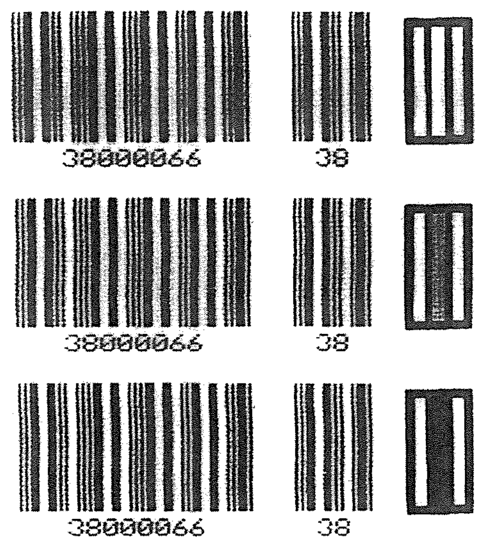



*Figure 3* An example of a TTI label showing the three main sections. The third section simulates the decreased reflectance of the active indicator material over time.

time (the rate of darkening increasing with increasing temperature), the percent reflectance value decreases and the permanent change in percent reflectance corresponds to the integrated thermal effect.

## *Transcontinental and transoceanic shipment*

### *Temperature history*

MRE rations were monitored under realistic transportation and storage conditions involving shipment from the ration assembler in McAllen,Texas to facilities in California, in Massachusetts, and in Turkey. Special MREs were obtained for this study in order to monitor ration components that are relatively sensitive to heat stress. They corresponded to 4 of the 12 available menus, each having one of the following entree items: omelet with ham, chicken-a-la-king, beef and rice meatballs in spicy tomato sauce, and escalloped potatoes with ham. Consequently, each case contained 12 meals, with the four menus in triplicate.

Two TTI models (MC11 and MC18) were placed in duplicate inside and outside the outer carton, providing a total of eight TTI labels for each case. The labels were scanned prior to applying them to the cases to obtain the initial reflectance measurements.

A total of 64 cases were shipped from the assembler: 24 to George Air Force Base (AFB) in California; 24 to an AFB in Incirlik, Turkey; and 16 to the Natick RD&E Center in Massachusetts for use as controls. Temperature recorders were included in some of the cases to obtain a history of temperature changes, based on readings taken every 2 h. The two AFB locations were very similar in average temperature, being 68.9 and 68.6°F for California and Turkey, respectively, but they had very different temperature profiles during the 31 Aug 1988 to 7 Sep 1989 time period.

The results of the long-term temperature histories are shown in Figure 4 for cases shipped to California. The rations were shipped by the assembler at the end of the summertime, Day 0 corresponding to 31 Aug 1988. Figures 5a and 5b show a more detailed rendering of the early temperature profile for these shipments, including the high tem-

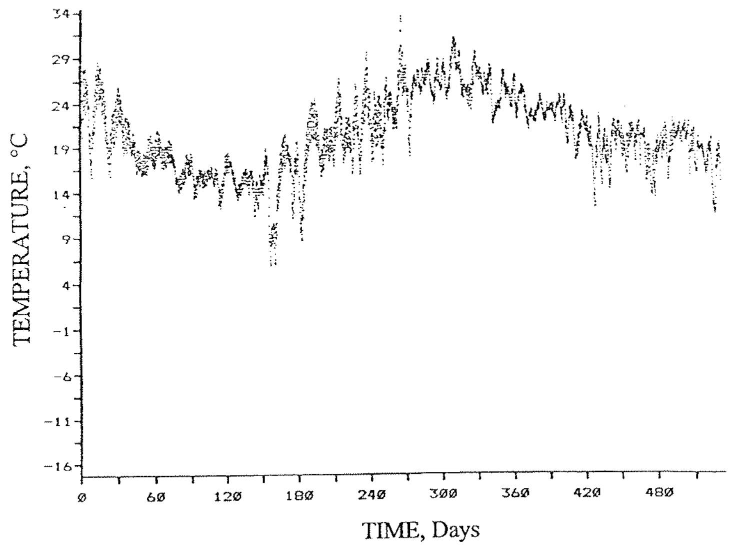



*Figure 4* Temperature profile recorded for MREs stored at George AFB, CA, for over a year showing the seasonal variations.

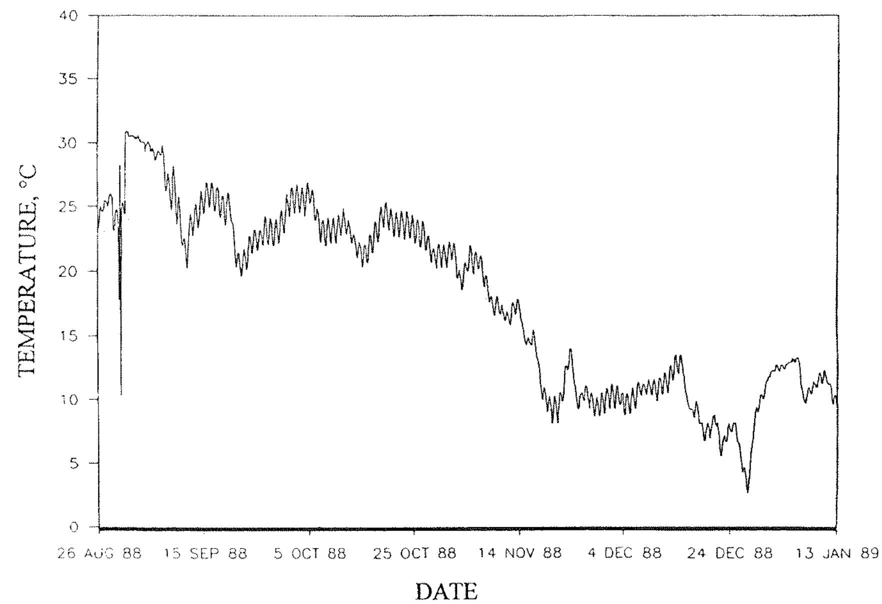
peratures encountered during transport by ship to Turkey. The daily fluctations (i.e., highs and lows) are evident in these printouts.

Some cases of rations stored in California and Turkey were returned at selected time intervals to Natick for scanning of the TTI labels. After 1 year in storage, the remainder of the rations were returned to Natick for scanning and sensory evaluation. For the rations shipped to and stored at George AFB, Figure 6 shows both the temperature profile from the digital recorder and the reflectance measurements from the TTIs. Although only four readings of the TTIs were made, they are consistent with the thermal history. The lines connecting the readings are steepest during the hotter months and least steep during the colder season of the year, corresponding to a slower rate of reaction for the polymerization. Table 1 gives the results of the TTI measurements for samples stored in California and Turkey for up to 13 months and then returned to Natick.

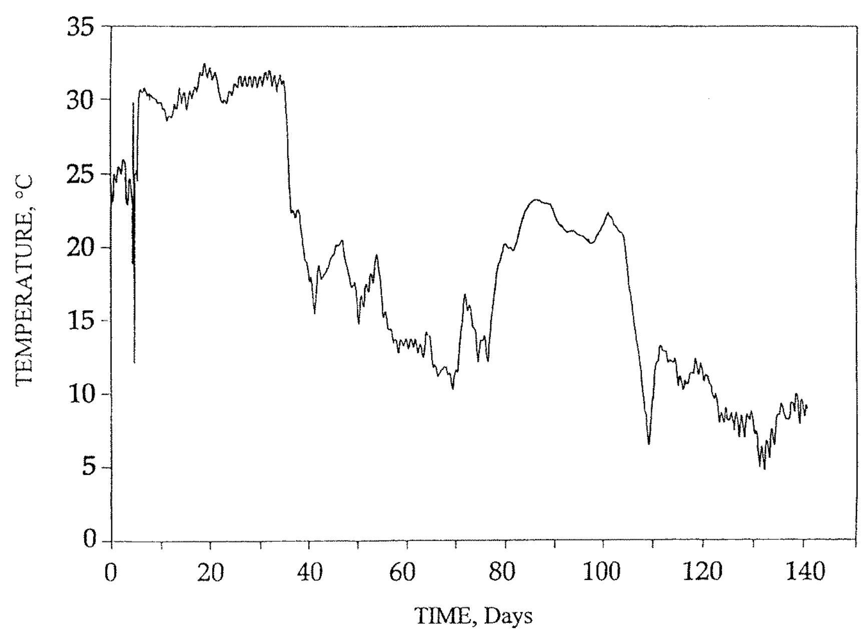
### *Product quality correlation*

A limited attempt at correlating MRE product quality with the temperature integration, expressed as percent reflectance, was successful and is instructive. The correlations involved MREs stored under constant temperature conditions at Natick where the TTIs could be scanned monthly and quality evaluations could be made by a sensory panel.

Sensory panel evaluations were conducted on products stored at 70°F and 100°F. Products included omelet with ham, chicken-a-la-king, beef and rice meatballs in spicy tomato sauce, escalloped potatoes with ham, potato au gratin, pears, and peaches. It was not expected that all items would show effects that could be correlated with the percent reflectance measurements or would change at rates that could be observed either because of the temperatures involved or because of the elapsed time at which the evaluations were made. Storage data at 70°F did not prove to be useful because of the short storage time. The data at 100°F, however, was useful for assessing the omelet, chicken, meatballs, escalloped potatoes, and pears.




(a)




(b)

*Figure 5* (a) Temperature profile recorded for MREs stored at George AFB, CA, showing on an expanded scale the daily cycling and the general decrease during the fall and early winter seasons. (b) Temperature profile recorded for MREs shipped to Incirlik, Turkey. Day 0 corresponds to 26 August 1988. It shows the general decrease during the fall season along with a higher temperature period at about 80–100 days when the rations were aboard ship.

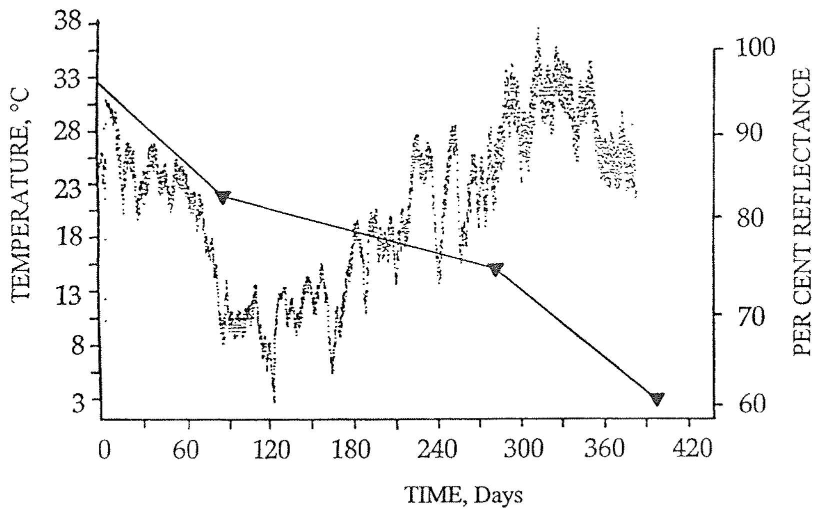



*Figure 6* The temperature profile for MREs stored at George AFB, CA, and the percent reflectance of the TTIs both plotted as a function of time. The slope of the lines connecting the percent reflectance measurements clearly changes in accordance with the seasonal variation in temperature.

**Table 1** Percent Reflectances for California (CA) and Turkey (T) Shipments

| Time (Months) | MC11 CA | MC11 T | MC18 CA | MC18 T |
|---|---|---|---|---|
| 0 | 96 | 96 | 92 | 92 |
| 2 | 84 | — | 48 | — |
| 9 | 74 | 67 | 22 | 15 |
| 13 | 59 | 61 | 2 | 7 |

The results for pears from MRE Menu #9 and for omelet with ham from Menu #4 are illustrative. These were stored at 100°F for over 2 years and rated for color and overall acceptance, respectively, after withdrawals at 2, 14, and 26 months. Panelists evaluated these using an open-ended magnitude estimation scale in which high scores are favorable. As the comparisons of percent reflectance with sensory scores over time in Figures 7 and 8 show, the correlations are qualitatively good. Since the scales for sensory scores were "stretched" so the 2-month value would coincide with the reflectance curve, the other values indicate a relative, not a quantitative, match. Moreover, reflectance readings below 20% (corresponding to extensive polymerization) do not provide an adequate basis for assessing the strength of the correlation. The correspondence in these plots, nevertheless, is clear and indicates that the TTIs can be matched to either subjective or objective assessments of quality.

## *Container vans in a desert environment*

### *Temperature history*

Three container vans, each with a different type of packaged ration, were transported to the U.S. Army Yuma Proving Ground for use in studying ration storage in a high-temperature desert environment. One van contained cases of MREs; another contained cases of T-rations, which are meal components thermoprocessed in metal trays suitable

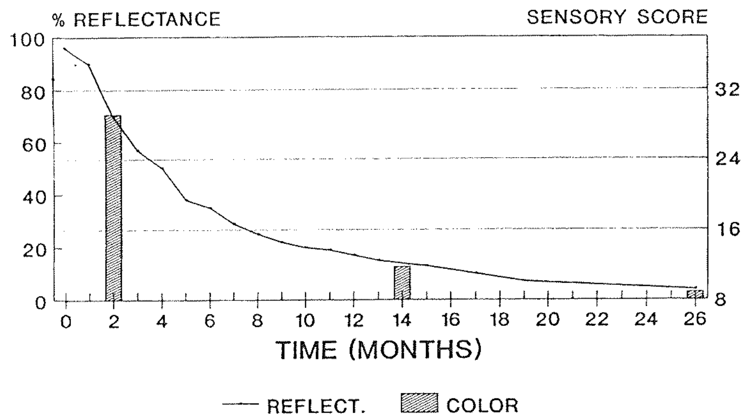



*Figure 7* Percent reflectance readings and sensory scores for color plotted as a function of time for MRE pears stored at 100°F. The sensory scale has been adjusted to make the 2-month score coincident with the line for the reflectance readings in order to show the close correspondence.

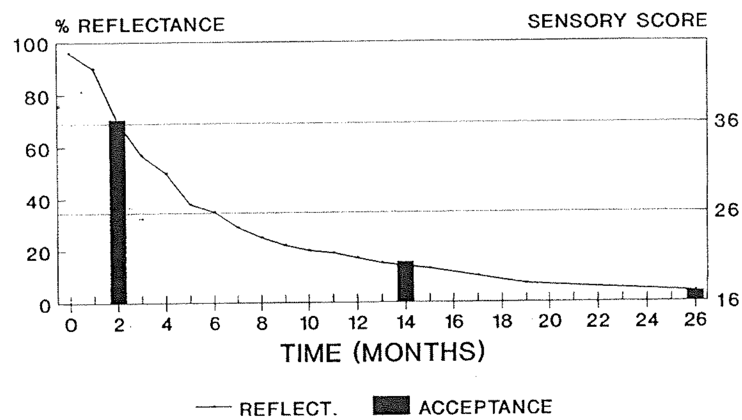



*Figure 8* Percent reflectance readings and sensory scores for overall acceptance plotted as a function of time for MRE omelet with ham stored at 100°F. The sensory scale has been adjusted to make the 2-month score coincident with the line for the reflectance readings in order to show the close correspondence.

for serving a group of 18 individuals; and the third contained cases of B-rations, which are a mix of dry and canned items, also suitable for group serving. These vans were 8' × 8' × 40' in size, with the capacity to hold a large quantity of rations for transportation and storage. It was possible to equip a small number of cases within a van for temperature monitoring and still have a van with the mass and other characteristics typical of a loaded van.

A total of 64 thermocouples and TTI labels were placed at selected locations in the vans. Most of the thermocouples were in the central van, containing the MREs; two thermocouples were placed on the outside of the van for comparison with the inside van temperatures and with local weather records. The daily temperature variations for a 2-week period that includes the hottest day of the year are shown in Figure 9.

Some of the TTI labels were placed near thermocouples for comparison. Table 2 shows the TTI percent reflectance measurements for labels with both MC11 and MC18 temperature sensitivities attached to cases placed in similar locations (southwest corner of the

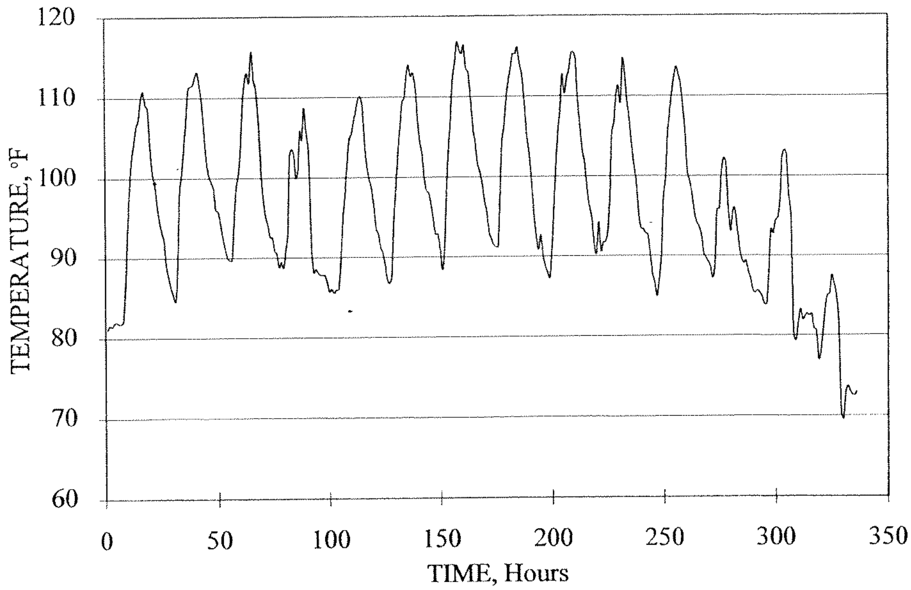



*Figure 9* Temperatures at Yuma Proving Ground recorded from a location about 20 ft away from the vans during a 2-week period in August 1992 showing the cyclic nature of the variations.

*Table 2* Comparison of Mean Reflectances for Similar Locations in Three Vans

| | B-Ration Van | | T-Ration Van | | MRE Van | |
|---|---|---|---|---|---|---|
| Indicator | MC18 | MC11 | MC18 | MC11 | MC18 | MC-11 |
| June | 94 | 95 | 96 | 94 | 95 | 95 |
| July | 5 | 40 | 19 | 54 | 9 | 52 |
| August | NA | NA | NA | NA | 1 | 38 |
| September | 3 | 12 | 3 | 24 | 5 | 31 |

*Table 3* Percent Reflectances from MC11 in the MRE Van

| | Van Top | | | | | | Van Bottom | |
|---|---|---|---|---|---|---|---|---|
| | South Side | | | North Side | | | South | North |
| AT[a] | 27 | 31 | 46 | 43 | 50 | 52 | 45 | 51 |
| TIME[b] | | | | | | | | |
| 0 | 95 | 95 | 95 | 95 | 95 | 95 | 96 | 95 |
| 1 | 52 | 51 | 46 | 49 | 58 | 47 | 59 | — |
| 2 | 38 | 34 | 27 | 36 | — | 29 | 48 | — |
| 3 | 31 | 22 | 19 | 22 | 37 | 19 | 45 | 43 |
| 10 | 19 | 16 | 10 | — | 21 | 15 | 37 | — |
| 11 | 15 | 11 | 9 | — | 18 | 12 | 32 | 32 |
| 13 | 9 | 8 | 7 | 7 | 11 | 7 | 23 | 27 |
| 16 | 8 | 3 | 2 | 5 | 4 | 4 | 19 | 16 |
| 17 | 4 | 3 | 2 | 3 | 3 | 1 | 16 | — |

[a] The number of the associated thermocouple for the TTI labels whose average percent reflectances are given.

[b] Time in months.

van) in the B, T, and MRE vans. The rate of change in reflectance is faster for the MC18 label than it is for the MC11. After one summer of exposure, the MC18 label had expired, the residual reflectance being about 10% or less. (Although it was not suitable here, this label can still be a useful indicator for short monitoring periods that might include the initial transportation of items to a warehouse.) The MC11 July and September readings are both lower for the B van than for the other two vans, which can be attributed in part to the differences in the color of the vans. Since the B van was darker, a higher average temperature was attained, resulting in lower reflectance readings.

Table 3 summarizes the percent reflectance measurements of the MC11 TTIs in the MRE van taken over 17 months. As expected, TTI label readings in the top sections of the van decreased more rapidly than those in the two bottom sections, and generally the TTI labels picked up differences throughout the van. These results show that it is possible to use TTI labels where it would be impractical to use a large number of thermocouples in order to monitor the storage environment and thus to reflect the condition of the products in all parts of a van or a similar storage space.

### *Product quality correlation*

Another attempt was made to correlate product quality with reflectance readings, this time using TTI data from the uncontrolled storage of MREs in the vans and using both instrumental and sensory evaluations of various quality attributes. MRE applesauce, cheese spread, escalloped potatoes with ham, grape jelly, and peanut butter were selected for comparison. All were subjected to the 3 months of summer stress at Yuma Proving Ground. The results on correlating color change in the applesauce and cheese spread with TTI reflectance are illustative and instructive.

The basic approach is based on the premise that both the degradation of a particular quality attribute and the decrease in TTI reflectance essentially follow first-order kinetics and that both the label and the product experience essentially the same temperature history. Consequently, at any point in time, the measurements of TTI reflectance and quality attribute should correspond to the integrated effect of that temperature history and should bear a clear relationship to each other. Since the activation energies for both processes could be different, the correspondence is not expected to be one-to-one. Nevertheless, in the simplest case, the fractional change in a particular attribute should be proportional to the fractional change in TTI reflectance. This concept is similar to the concept used in relating bacterial destruction to the formation of chemical markers in thermoprocessed foods.[12–13]

In applying this concept to the degradation of color of MRE applesauce and cheese spread, certain simplifications and estimations had to be made, because measurements of TTI reflectance and product color were not always made at identical times. Reflectance readings were made initially and at 1, 2, and 3 months afterwards, whereas instrumental color measurements, $a^*$ and $L$ values, were made initially and at 3, 12, 24, and 36 months afterwards. To obtain color measurements comparable in time to the TTI reflectance measurements, plots of $a^*$ and $L$ vs. time were made for both applesauce and cheese spread, and then fitted with curves that accommodated well the more significant changes that took place over the first 12 months. The $a^*$ and $L$ values for each product at months 1, 2, and 3 were then calculated from the fit and used in making the correlation with TTI reflection.

As Figures 10 and 11 indicate, the correlation of instrumentally determined color change in applesauce and cheese spread with reflectance is relatively good. For both products, the $a^*$ values, which measure the degree of redness, for both products linearly correlate with the TTI reflectance, expressed as the ratio of reflectance at any time to the

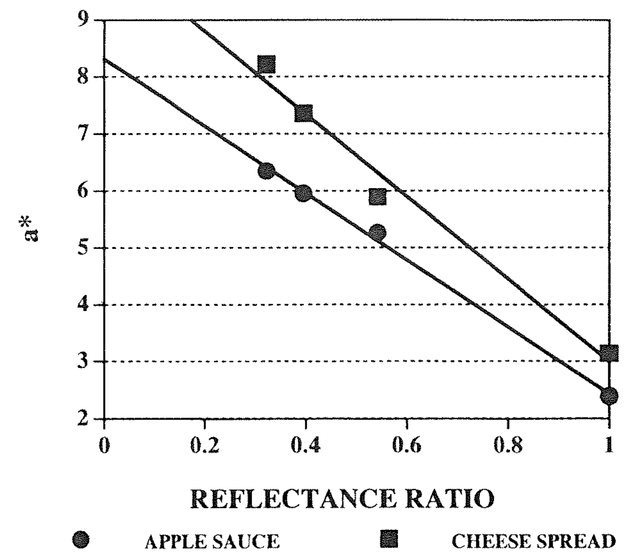



*Figure 10* Measured $a^*$ values from stored samples of applesauce and cheese spread plotted as a function of the ratio of the TTI reflectance at time of withdrawal to its initial reflectance.

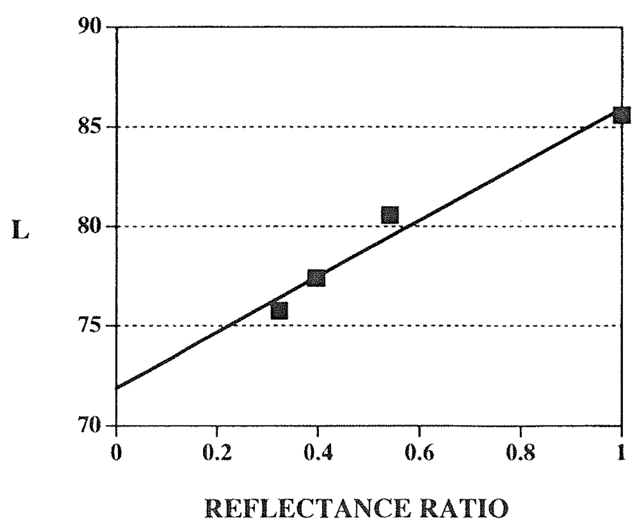



*Figure 11* Measured or extrapolated $L$ value for cheese spread plotted as a function of the ratio of the TTI reflectance at time of withdrawal to its initial reflectance.

initial reflectance. The redness intensity increases with time and the reflectance decreases with time, so the correlations shown in Figure 10 are negative. The separation of the two lines is primarily a consequence of different absolute values of $a^*$. The $L$ value for cheese spread (Figure 11) also correlates well with the ratio of TTI reflectances. Since it is a measure of lightness and darkness and the product became darker with time, the correlation of $L$ with the ratio of TTI reflectances is positive. It must be acknowledged that the correlations here are rough, in part because the values of $a^*$ and $L$ for 1, 2, and 3 months were obtained by fitting data, most of which pertain to times up to 36 months. Despite this necessity, the inference is clear that the TTIs, if properly chosen and calibrated for a particular attribute, give useful information about product quality.

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